Presented at IPC Printed Circuits Expo®
SMEMA Council APEX®
Designers Summit 04

Lead and Lead-free Solder Project LCIA Characterization Methods

Maria Leet Socolof, Jack R. Geibig and Mary B. Swanson
University of Tennessee,
Center for Clean Products and Clean Technologies
Knoxville, TN

Abstract
This paper describes the life-cycle impact assessment methodology developed by the University of Tennessee to calculate the impacts resulting from the use of lead and lead-free solders during the manufacture and assembly of electronics. Formulas for calculating individual impact categories are presented and briefly discussed. Actual impact scores resulting from the application of this methodology within the LCA research being conducted as part of the Lead Free Solder Partnership are currently being reviewed and will be presented in detail in a future publication.

Introduction
Due to its known toxicity to human health and the environment, lead and lead-containing products increasingly have come under regulatory scrutiny by several countries, including members of the European Union and Japan. This scrutiny is based primarily on assumptions that the use of lead in products will eventually result in exposure and resulting harm to human health and the environment. However, to-date there has been little scientific research conducted to identify and assess the potential impacts resulting from the use of lead-based solders in electronics, and even less about the prospective lead-free solder alternatives.

In response, the University of Tennessee Center for Clean Products and Clean Technologies has partnered with the U.S. EPA Design for the Environment Program, non-governmental organizations, and prominent members of the North American electronics industry and their suppliers in a project to evaluate the life-cycle environmental and human health impacts resulting from the use of lead and lead-free solders in electronics. The primary goal of the research is to conduct a life-cycle assessment (LCA) of lead-based solder and leading lead-free alternatives that considers impacts associated with the entire product system.

LCA is a comprehensive method for evaluating the full life cycle of a product system, from materials extraction and processing to manufacture, use and disposal of the product at the end of its useful life. In an LCA, inputs and outputs of each unit process within the product system are inventoried (called the life-cycle inventory or LCI) and then used to characterize the potential impacts through the performance of a life-cycle impacts assessment (LCIA). This paper presents the methodology used by the University of Tennessee in the lead and lead-free solder LCA to calculate environmental and human health impacts. Actual impact scores for each of the solders being evaluated in the LCA are currently undergoing review by an advisory committee and thus are not included here. LCA results will be published a draft document to be released for review later this year.

Life-Cycle Impact Assessment Method
LCIA involves the classification of inventory data into impact categories and the subsequent characterization of impacts.[1, 2, 4, 10, 12] Algorithms for some impact categories are commonly accepted by the LCA community and these algorithms use generally agreed upon values for quantifying impacts. For example, global warming impacts are calculated for a set of chemicals that have global warming potentials, which are based on the radiative forcing of greenhouse gases in the atmosphere.[11] Classification and characterization of other impact categories are much less standard, especially toxic impacts. In recent years, life-cycle assessment (LCA) practitioners have been incorporating toxicity impacts into LCAs as warranted. However, no consensus has been reached as to which method might be adopted by a majority of the LCIA community. The various methods each have their own set of strengths and weaknesses and toxicity impact methodologies continue to evolve.[5, 6, 7, 8, 9, 13, 14, 17]

This section describes characterization methods for sixteen life-cycle impact categories in the lead-free solder project (LFSP). The impact assessment methodology used in the LFSP calculates impacts for a number of impact categories, including several traditional LCA impact categories (e.g., global warming, stratospheric ozone depletion, photochemical smog, energy consumption). The method also provides relative impact scores for potential chronic human health and aquatic ecotoxicity impacts. The more traditional categories use standardized methods commonly applied in LCAs. For toxicity impacts, the method used here employs a relatively comprehensive screening method as compared to some other methods.[17] Other, less traditional impact categories are also included, such as volume of landfill space use and water quality impacts. The sixteen impact categories used to evaluate life-cycle impacts in the LFSP are briefly described below. They are grouped under three general headings: natural resources, abiotic ecosystem impacts, and toxicity impacts).

Natural Resources

This group of impact categories includes non-renewable resource use, renewable resource use, energy use, and landfill space use.

Materials use

Non-renewable resource impact scores are based on the amount of material and fuel inputs of non-renewable materials. Renewable resource impact scores are based on process inputs in the life-cycle inventory of renewable materials, such as water or renewable fuels. The non-renewable and renewable impact scores are the amount of virgin material consumed in the life cycle. Impact scores are in units of kilograms of material per functional unit, which is 1,000 cubic centimeters of an alloy as applied to a printed wiring board in the LFSP.

Energy use

General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy impacts are based on both fuel and electricity inputs and are reported in megajoules (MJ) of energy per functional unit.

Landfill space use

This pertains to the use of suitable and designated landfill space as a natural resource. It includes both hazardous and solid waste landfill space. The impact scores are calculated using the mass amount of solid and hazardous waste outputs disposed of in a landfill. Using the approximate density of the waste, the mass is converted to a volume of landfill space used. The landfill space use impact score is reported in cubic meters of waste per functional unit.

Abiotic Ecosystem Impacts

Abiotic ecosystems refer to the non-living environment that supports living systems. This includes global and regional atmospheric impacts and potential degradation of water and land. The LFSP LCIA methodology includes the following abiotic ecosystem impacts: global warming, stratospheric ozone depletion, photochemical smog, acidification, air quality (particulate matter loading). Most abiotic environmental impacts are calculated using equivalency factors that are applied to the inventory data. Equivalency factors are values that provide a relative score or weighting that relate an inventory output amount to some impact category relative to a certain chemical. For example, to relate an atmospheric release to the global warming impact category, chemical-specific global warming potential (GWP) equivlancy factors are used. GWPs are a measure of the possible warming effect on the earth's surface arising from the emission of a gas relative to carbon dioxide. They are based on atmospheric lifetimes and radiative forcing of different greenhouse gases. The air quality category, on the other hand, is a simple mass loading of particulate matter released to the atmosphere and does not include an equivalency factor calculation.

Global atmospheric impacts

Global warming and stratospheric ozone depletion represent global abiotic impacts. Both are calculated using equivalency factors: GWP for global warming and ozone depletion potential (ODP) for stratospheric ozone depletion. For any chemical output in the life-cycle inventory for which there is a GWP, the inventory amount of that chemical is multiplied by the GWP (in CO_2-equivalents, over a 100 year time horizon) to calculate a global warming impact score for that chemical. The life-cycle global warming impacts are the sum of all chemical-specific global warming impact scores. Similarly, chemicals with an ODP (in CFC-11-equivalents) are used to calculate the ozone depletion impacts. The output inventory amount of an ozone-depleting chemical is multiplied by the ODP equivalency factor to calculate an impact score. The final impact scores are provided in kilograms of CO2-equivalents or CFC-11-equivalents.

Regional atmospheric impacts

This group of impact categories includes photochemical smog, acidification, and air quality (particulate loading). Impact scores for the first two categories are based on the identity and amount of smog-creating or acidification chemicals released to the air using equivalency factors. For photochemical smog, chemicals with a photochemical oxidant creation potential (POCP, in ethane-equivalents) are used to calculate life-cycle impacts. The POCP equivalency factor is multiplied by the inventory output amount of any chemicals in the inventory that have a POCP. The resulting impact score for each chemical is added across all POCP chemicals in the inventory to estimate a photochemical smog life-cycle impact. Similarly, an acidification potential, measured in SO_2-equivalents represents the equivalency factor for acidification impacts. The acidification potential is multiplied by the inventory output amount of chemicals released to the environment that have the potential to create air acidification and are presented in SO_2-equivalents per functional unit.

Air quality is measured as air particulate loading. This refers to the release and build-up of particulate matter, primarily from combustion processes. The impacts are based on release amounts to the atmosphere. The sum of the mass loading of particulates across the life cycle equals the air particulate (or air quality) impact score.

Water quality impacts
This category includes nutrient enrichment (eutrophication) and local water quality impacts. Eutrhophication impacts are based on the eutrophpication potential (EP, in phosphate-equivalents). The EP times the inventory amount provides the impact score for eutrophication in kilograms of phosphate-equivalents per functional unit.

Local water quality impact scores are based on the identity and quantities of wastewater/water quality parameters (biological oxygen demand [BOD] and total solids). This impact category is scored as a mass loading of BOD and solids per functional unit.

Toxicity Impacts
Toxicity impacts include both human and ecological toxicity categories. The human health impacts include chronic non-cancer impacts to occupational workers, cancer impacts to occupational workers, chronic non-cancer impacts to the general public, and cancer impacts to the general public. The ecological toxicity impacts are represented by an aquatic ecotoxicity impact category. Terrestrial ecotoxicity is not included as a separate impact category as the screening methodology would generate the same results for terrestrial toxicity as it would for human non-cancer impacts.

The toxicity impact categories use a hazard value (HV) method which was developed at the UT Center for Clean Products and Clean Technologies and is based on the inherent toxicity of a chemical. It uses the concept of chemical ranking and scoring[16] to develop hazard values to measure the relative toxicity of a chemical. The original ranking method, upon which this HV method is based, [15] was updated for use in life-cycle assessment.[13, 14] The HV approach uses basic toxicity data (e.g., no observed adverse effect level [NOAELs], cancer slope factors) to develop HVs which are applied to life-cycle inventory data to calculate impact scores. The hazard values rank the inherent toxicity of a chemical based on its toxicity relative to a geometric mean for a particular toxic endpoint. It is a relatively simple model not intended to model details of fate and transport (which is often difficult given the spatial and temporal limitations of LCI data), but to screen inventory data for potential toxicity impacts. This HV approach isused for all the toxicity impact categories described herein.

Using the HV approach, the first step for calculating life-cycle toxic impacts is to review the life-cycle inventory to determine which outputs can be identified as non-toxic. For example, chemicals such as those “Generally Accepted as Safe” by the U.S. Food and Drug Administration are considered for listing as non-toxic. In addition, materials considered as nutrients, (e.g., calcium, chloride) would be considered non-toxic.[3] Chemicals remaining in the inventory are classified as potentially toxic and used to calculate impacts, whether or not toxicity data are available for the chemical. The HV method allows the LCIA to use default values for chemicals that lack toxicity data.

The toxicity of a chemical is represented as a relative ranking compared to other chemicals. For chronic non-cancer effects, the NOAEL or the lowest observed adverse effect level (LOAEL) is the toxicity data point of choice. For cancer effects, slope factors (SF) and weight of evidence (WOE) are used to determine the hazard values. Aquatic ecotoxicity hazard values are characterized by fish LC_{50} (lethal concentration to 50% of an exposed population) and fish NOEL (no observed effect level) values. For each impact category (non-cancer, cancer, and aquatic ecotoxicity), the toxicity value for a particular endpoint (e.g., inhalation NOAEL) is normalized by the geometric mean of that endpoint for a number of chemicals. Table 1 lists the number of chemicals (n) and the geometric mean calculated for those chemicals for each endpoint. The toxicity endpoint data were collected from the literature, as documented in Socolof et al. (2001), Appendix K.[14]

A hazard value for human chronic non-cancer impacts (HVnc) is calculated to represent the relative non-cancer toxicity of chemical *i*, using the reciprocal of the NOAEL compared to the reciprocal of the geometric mean (gm) of the NOAELs:

$$HV_{nc,i} = (1/NOAEL_i) / (1/NOAEL_{gm}).$$

Table 1 - Geometric means used for calculating HVs

Endpoint	n	Geometric mean
Inhalation NOAEL	84	68.7 mg/m^3
Oral NOAEL	160	14 .0 mg/kg-day
Inhalation SF	105	1.70 $(mg/kg\text{-}day)^{-1}$
Oral SF	175	0.71 $(mg/kg\text{-}day)^{-1}$
Fish LC_{50}	221	24.6 mg/L
Fish NOEL	199	3.90 mg/L

This results in a hazard value that increases with increasing toxicity. When an inhalation or oral NOAEL is used, the geometric mean for the respective route of exposure is used to calculate the HV (see Table 1). In the case where a LOAEL, but not a NOAEL, is available for a chemical, the LOAEL/10 is used in place of the NOAEL of chemical *i*.

For potentially toxic chemicals with unavailable toxicity data, the chemical's toxicity is assumed to equal the geometric mean. Therefore, the hazard values are given a value of one to represent an average toxicity.

For cancer impacts, cancer SFs, developed through the U.S. EPA, are used to rank the relative toxicity. Because slope factors are reciprocal units of dose, the HV is simply the quotient of the SF for the chemical of interest (*i*) and the geometric mean (gm) of all available slope factors:

$HVca,i = SFi / SFgm.$

For chemicals that have no slope factor, but have a cancer WOE designation by either EPA or the International Agency for Research on Cancer (IARC), either a default HV of one or zero is given, depending on the WOE. Chemicals designated as not classifiable, non-carcinogenic, or probably non-carcinogenic are given HVs of zero. All others (possible, probably, or known human carcinogens) are given the default of one, meaning the potential carcinogenicity is assumed to be equivalent to the geometric mean of the chemicals for which there are slope factors.[14]

The aquatic toxicity impact hazard value is calculated similarly to the non-cancer human impacts, except that both acute and chronic endpoints are considered and summed:

$HVaq,i = \{(1/LC_{50}i)/(1/LC_{50}gm)\}+\{(1/NOELi)/ (1/NOELgm)\}.$

Conclusions

Each of the sixteen impact categories that are used to estimate life-cycle impacts of the lead and lead-free solders are presented as individual impact categories. There is no attempt to aggregate the scores together to represent one life-cycle impact score for all impacts of a solder alloy. As all impacts are presented independently, there is no use for weighting of the impact categories. If users of the study results have preferences as to the importance of a particular impact category over another, then they are able to identify those interest areas and make decisions based on the results as appropriate for their needs.

The LFSP results as will be presented in the final Lead and Lead-free solder LCA will present categories with equal weighting. Comparisons among alloys can be made for each impact category. The results will also show the number of impact categories in which an alloy may have greater impacts over others for a each impact category. Other uses of the LCIA results are to identify major drivers within each alloy's impacts. These drivers can be identified as largest contributing life-cycle stage, process, or individual material and can be used when trying to make seek environmental improvement opportunities.

Acknowedgements
The authors would like to acknowledge the U.S. EPA Design for the Environment Program, Intel Corp., Thomson Consumer Electronics, Delphi-Delco, Agilent Technologies, Cookson Electronics, Hewlett-Packard, IBM, Pitney Bowes, Rockwell Collins, and International Sematech for financial support of this research.

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The draft report will be available at the following url
http://eerc.ra.utk.edu/ccpct/lfsp.html